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## **Virtobot 2.0: the future of automated surface documentation and CT-guided needle placement in forensic medicine**

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# Virtobot 2.0: the future of automated surface documentation and CT-guided needle placement in forensic medicine

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**Abstract** In this paper we present the second prototype of a robotic system to be used in forensic medicine. The system is capable of performing automated surface documentation using photogrammetry, optical surface scanning and image-guided, post-mortem needle placement for tissue sampling, liquid sampling, or the placement of guide wires. The upgraded system includes workflow optimizations, an automatic tool-change mechanism, a new software module for trajectory planning and a fully automatic computed tomography-data-set registration algorithm. We tested the placement accuracy of the system by using a needle phantom with radiopaque markers as targets. The system is routinely used for surface documentation and resulted in 24 surface documentations over the course of 11 months. We performed accuracy tests for needle placement using a biopsy phantom, and the Virtobot placed introducer needles with an accuracy of 1.4 mm ( $\pm 0.9$  mm). The second prototype of the Virtobot system is an upgrade of the first prototype but mainly focuses on streamlining the workflow and increasing the level of automation and

also has an easier user interface. These upgrades make the Virtobot a potentially valuable tool for case documentation in a scalpel-free setting that uses purely imaging techniques and minimally invasive procedures and is the next step toward the future of virtual autopsy.

**Keywords** Virtopsy · Forensic imaging · Surface scanning · Image guided · Needle placement · CT · Robotic

## Introduction

Imaging technologies become increasingly important in forensic death examinations, and these technologies are important enough for the Committee on Identifying the Needs of the Forensic Science Community of the National Research Council in the US to recommend the “implementation of specialized imaging techniques” for medicolegal examinations [1]. In Switzerland, the Virtopsy project aims to integrate modern imaging techniques such as computed tomography (CT), magnetic resonance imaging (MRI), 3D surface scanning, and photogrammetry into the workflow of a forensic medical investigation [2]. While these techniques allow for the gathering of objective evidence that can be beneficial to the investigation, they also tend to be time consuming. To address this issue, we developed a prototype of a robotic system that automated tasks that were either repetitive or required high accuracy within the field of forensic imaging. The first prototype of the system, the Virtobot, was developed at the Institute of Forensic Medicine in Bern, Switzerland in 2007 [3]. This first Virtobot was capable of performing fully automated 3D surface scans using an optical surface scanner and CT-guided placement of co-axial introducer needles for tissue or liquid sampling.

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## Surface scanning

Surface scanning decreases the gap between the three-dimensional (3D), low resolution, colorless datasets that are generated by CT scanners and colored, two-dimensional (2D) surface documentation that is provided by photography. To generate a high-resolution, textured surface documentation, a two-step approach is utilized [4]. In the first step, photogrammetry reference markers are applied to the body, and a series of digital photos are taken from different positions. Based on the photos, the exact coordinates of the markers in 3D space can be calculated to prepare for actual 3D surface scanning. Additionally, the photos can be used to apply color information to the surface scans. In the second step, the surface scanner is used to document the geometric properties of the deceased. Because the volume of the surface scanner is not large enough to sufficiently scan the entire body in only one scan, several scans must be fused. The positional information of the reference markers that has been calculated during photogrammetry is used in this process. By detecting all markers in its field of view and comparing them to the positioning that is gathered during photogrammetry, the surface scanner software can estimate the actual scanning position relative to the body.

Surface scanning data can be fused with CT datasets for complete internal and external documentation of the body. When combined with other data such as laser scans of incident scenes, this allows for virtual reconstructions such as 3D visualizations [5, 6].

We demonstrated a method for automating the surface documentation procedure using the first prototype of the Virtobot. With regards to surface scanning, its suboptimal workflow, the fact that photogrammetry had to be performed manually, and the semi-automatic tool change, were limitations of that prototype.

## Post-mortem biopsy

Histological examinations can play an important role in forensic investigations. If no autopsy is performed after imaging or radiologically conspicuous focal organ changes have to be retrieved, the required tissue samples can be gathered using minimally invasive needle biopsy techniques, which helps to overcome some of the limitations of imaging [7, 8]. For pulmonary fat embolism, pneumonia, and sepsis, tissue samples that are gathered using needle biopsies have shown high diagnostic performance [9, 10]. Furthermore, the minimally invasive, post-mortem needle biopsy has been more accepted by the next of kin than autopsy procedures [11]. To sample focal organ changes that are visible by imaging, accurate, image-guided needle placement is required, and different techniques exist to

accomplish this type of sampling, such as manual, navigated, and robotic CT-guided needle placement and ultrasonography guidance [3, 10, 12, 13].

It was possible to plan needle trajectories based on CT datasets and place them automatically under the supervision of a surgical navigation system using the first version of the Virtobot. However, the main drawback of the previous system was the necessity to register the CT dataset to the body by defining landmarks using the P&N and pointing at these landmarks using a tracked surgical pointer [3]. This time-consuming and unintuitive task reduced the acceptance of using the robot for needle placement during routine examinations. Additionally, using active optical tracking [light emitting diodes (LED) that are being tracked as opposed to reflective markers in passive tracking systems] to determine the position of the body and the robot makes the system more expensive and requires additional cables for every tool that is involved.

In this article, we describe how we addressed the issues that were identified for the first prototype of the Virtobot system when developing a second prototype. The upgraded system includes workflow optimizations, an automatic tool-change mechanism, a new software module for trajectory planning and a fully automatic CT-data-set registration algorithm. A video demonstrating the workflow can be viewed at [https://www.youtube.com/watch?v=Rd245p4AsoI&feature=youtu\\_gdata\\_player](https://www.youtube.com/watch?v=Rd245p4AsoI&feature=youtu_gdata_player) [14].

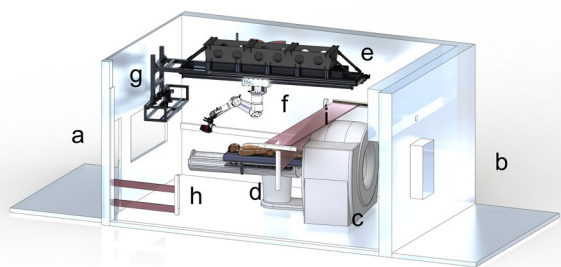
## Materials and methods

### General considerations: hardware

Our CT room is equipped with a Siemens Somatom Definition Flash (Siemens Healthcare, Erlangen Germany) Dual Source CT. Due to the spatial constraints of the CT scanner room, i.e. its small size ( $L \times W \times H$ : 6.5 m  $\times$  4.1 m  $\times$  3.6 m with a suspended ceiling, see Fig. 1), and the positioning of the CT table, the existing Virtobot system concept had to be adapted. To conserve space, we chose the space above the CT gantry as the parking position of the robotic arm (Fig. 2). While the position above the CT kept the working area free when the robot was not in use, it had to be elevated to fit between the ceiling and CT scanner. We achieved this by introducing an additional pneumatic lifting axis that could lift the robot base approximately 200 mm, which allowed the tool rack to be positioned higher and not block the view into the CT room. The fail-safe use of the lifting axis was guaranteed by a locking cylinder and monitored using safety switches. Lifting operations could only be performed at a specific position of the linear axis and at a certain robot pose. To avoid collisions between the robot and the housing of the

CT-gantry when moving the robot into the parking position, an additional light fence that was orientated horizontally and located just above the housing was included into the emergency stop circuit of the system. In contrast to the first system, a new generation of light fences for access control was used, which allowed for easier alignment of the components.

Robotic arms are usually calibrated to move to pre-taught positions with high accuracy, irrespective of the actual coordinates. In our setting, the robots orientation and position are given as absolute coordinates as calculated by the P&N. The robotic arm (Stäubli TX90L, Stäubli AG, Pfäffikon, Switzerland) was therefore calibrated for absolute positioning accuracy to allow for faster and more accurate needle placement by minimizing the number of correction movements that were required before inserting the needle.



**Fig. 1** Orthographic visualization of the CT room. *a* X-ray shielded working area, *b* engineering room, *c* CT gantry, *d* CT table, *e* external rail of the Virtobot, *f* Virtobot mounted on external axis with lifting mechanism, *g* tool stand with surface scanner, digital photo camera and biopsy module, *h* safety light fence for room entry control, and *i* safety light fence for device protection



**Fig. 2** Virtobot in parking position above the CT gantry. The screen in the background is connected to the computer running the Virtobot software

One major issue in the workflow of the first Virtobot was the use of a semi-automatic tool change. This tool change required the user to manually lock a tool and attach all cables (power and data) by hand. The second prototype of the Virtobot addressed this problem by introducing an automatic tool-changing mechanism. The specific tool-changing unit (Schunk SWS40, SCHUNK GmbH & Co. KG, Lauffen/Nekkar, Germany) provided pneumatically actuated, self-retaining locking of the selected robotic tool and was feed-through of the air supply and electric connections of the tool control or sensor input. Using this automatic changing system also allowed for out-of-reach mounting of the tool magazine (Fig. 3).

The robot controller box, the input/output terminal box, and the main safety controllers, were also positioned above the suspended ceiling. The main cabinet that included the system power supply and the controller for the linear axis was positioned in an engineering room that was situated beneath the Virtobot room. For aesthetic purposes, the external axis was integrated into the suspended ceiling and covered with a flexible cover.

The spatial constraints also required a new concept for robot motion; therefore, the robot pose reconfiguration was performed above the CT table. A dedicated motion-planning algorithm was implemented to provide coordinated motion of the robot and external axis. This new concept reduced the motion time of the robot by optimizing the planned robot path, and the algorithm automatically decided whether the robot and the linear axis could move simultaneously or must move consecutively to meet the narrow spatial situation. When using this more complex motion concept, improving the collision prevention mechanism by including a model of the relevant environment was also required. Therefore, emergency stop handling procedures were enhanced to handle these new constraints.



**Fig. 3** Tool stand during automatic tool change. *Left to right* surface scanner, digital photo camera for photogrammetry and biopsy module

In addition, a screen was mounted to the wall next to the CT table that displayed the content of the control computer screen and allowed for tracking output to be visualized, i.e. to check the registration accuracy using a surgical pointer.

#### General considerations: software

Different software packages were used for the first Virtobot: the Virtopsy Control Center (VCC) for coordinating the workflow and general data handling, the GOM Atos software for surface scanning, GOM Tritop for photogrammetry (both GOM mbH, Braunschweig, Germany) from photos that were manually taken prior to the surface scan, and planning and navigation software for biopsy trajectory planning and supervised execution. These dedicated software suites ran on different computers with different operating systems [Windows XP® (Microsoft Corp., Redmond, USA), Fedora Core (Red Hat, Inc., Raleigh, USA), and SUSE Linux (SUSE®, Nuremberg, Germany)]. To reduce the amount of involved computer hardware, we decided to utilize Windows 7 as a general platform for all involved programs so that the entire software could be run on one machine. The new Atos software ran under Windows 7 and combined the photogrammetry (previously called Tritop) and surface scanning capabilities. The planning and navigation software was redeveloped to support the new passive tracker, automatic registration and a simplified workflow and user interface. Similar to the first prototype of the Virtobot, the VCC remotely controlled all other dedicated programs by using network interfaces.

#### Surface documentation

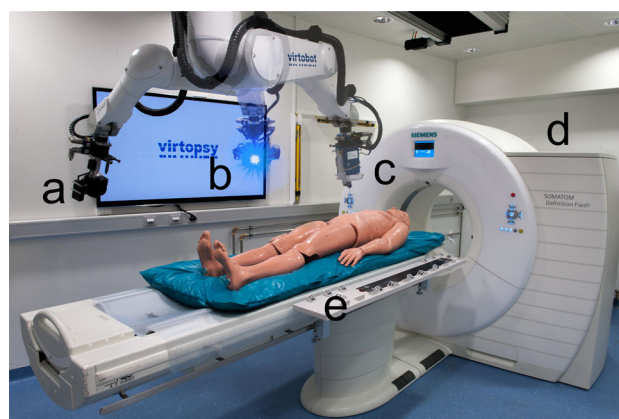
Surface documentation is performed for all cases that have a reconstructive question and visible injuries on the body surface. Bodies that are charred or are in a higher stage of decomposition are usually excluded.

The surface documentation procedure begins with the preparation of the body, which involves cleaning, hair removal at the areas of interest to reduce scanning artifacts, and, if necessary, the adaption of wounds to have a more defined wound pattern. Uncoded reference markers are applied to the body and later used for fusing the separate surface scans. The body is fixed by a vacuum mattress on the CT table to avoid movement during the scans and allow for fusion of the surface documentation with the subsequent CT scan.

The first step of the documentation procedure is photogrammetry (Fig. 4a), where the 3D position of the un-coded reference markers is calculated using a series of digital photos. Additionally, the photos can be used as textures for the polygon model that is generated by the surface scan. The presence of coded markers and scale bars

on some of the images is required as reference for calculating the positions of the un-coded reference markers. For the first prototype of the robot, coded markers and scale bars were manually placed on and around the body. To optimize this step, we built two wooden boards with integrated markers and scale bars that could be attached to the side rails of the CT table. The Virtobot automatically took photos from predefined locations using a Nikon D700 (Nikon Corporation, Tokyo, Japan) digital single-lens reflex (DSLR) camera with 12.1-megapixel resolution. The photos were then sent to the operating computer using a wireless local area network (WLAN) interface (Nikon WT-4, Nikon Corporation, Tokyo, Japan), and the images were automatically loaded to the ATOS software (ATOS Professional V7.5 SR2, GOM mbH, Braunschweig, Germany). Once all photos were taken, the 3D position of the un-coded reference markers was automatically calculated.

The second step of the documentation procedure is surface scanning (Fig. 4b). The current Virtobot is equipped with an optical surface scanner (Atos Compact Scan 5 m, GOM mbH, Braunschweig, Germany), which uses blue LED light and has a higher resolution and faster scanning times than the older ATOS III Rev. 01 (GOM mbH, Braunschweig, Germany). Similar to the first Virtobot, the surface scanner of the new Virtobot automatically scans the body from predefined positions but with decreased operation time. In addition, individual positions can be defined during the scanning procedure, and the different scans are automatically fused by the ATOS software by utilizing the positional information of the coded reference markers.



**Fig. 4** Virtobot with different mounted tools. *a* Digital camera for photogrammetry, *b* surface scanner, and *c* biopsy module. A dual-source CT scanner (*d*) provides datasets that can be fused with surface data or used for planning needle trajectories. For increased working speed, a side board with integrated optical markers and scale bars can be attached to the side rail of the CT table (*e*)



## Biopsy

### Hardware

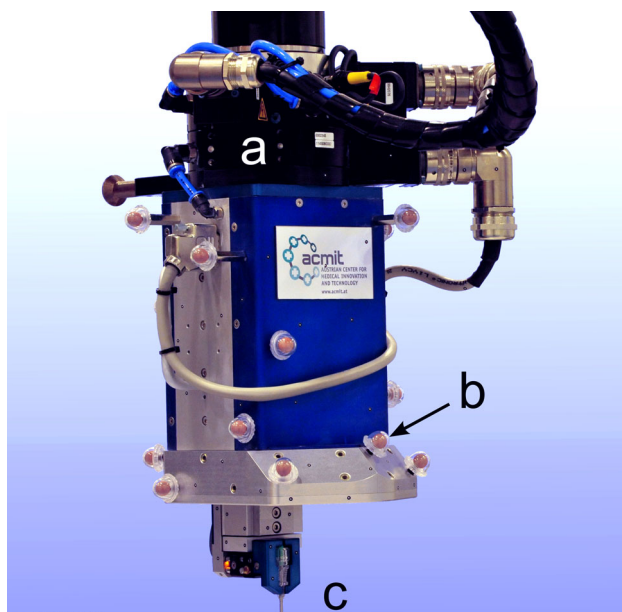
We used a custom-made biopsy module (Integrated Microsystems Austria GmbH, Wiener Neustadt, Austria) that could be mounted onto the robot (Figs. 4c, 5). To reduce the cost and the amount of cables that were involved, we used a passive optical tracker (CamBar B2, Axios 3D, Oldenburg, Germany), which used passive reflective markers (SORT Markers, Atesos Medical AG, Aarau, Switzerland), instead of an active tracker that used LED. Nineteen reflective markers were integrated into the biopsy module, and the positions and normal of the markers were calibrated using an ATOS Triple Scan surface scanner (GOM mbH, Braunschweig, Germany). For referencing of the body, we developed marker stands that could be attached to the body and each held one reflective marker. Each marker stand contained a tungsten ball with a diameter of 0.8 mm that was located at the center of the reflective marker (Fig. 6). Because tungsten has a high X-ray density and, therefore, a high Hounsfield value, it can be easily detected by the navigation software, which automatically registers the CT dataset.

### Software

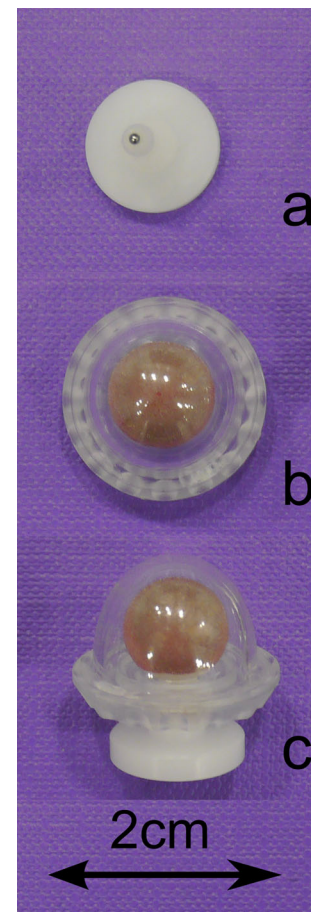
Two dedicated programs were involved in the planning and execution of the trajectories. The tool server integrated the

functionality of the tracker and offered a network interface for the planning and navigation software. Second, the planning and navigation station allowed for trajectory planning and could verify the position and orientation of the robot. Both programs were re-developed to run under Windows and offered an easier workflow. The following libraries were used for software development: Qt 4.8.2 (Digia, Helsinki, Finland) for the user interface and network support, VTK 5.10.0 (Kitware Inc., Clifton Park, New York, USA) for digital imaging and communication in medicine (DICOM) support and dataset visualization, and Metrology 2.0.196 (Axios 3D Services GmbH, Oldenburg, Germany) for the tracker integration. The planning and navigation software ran in 64 bit to support the loading of large datasets.

One of the major issues regarding the acceptance of a post-mortem biopsy was the complex user interface of the software. To make the software easier to operate, the user is now guided through the workflow step by step. After the CT transfers the dataset to the navigation computer, it is



**Fig. 5** Biopsy module of the Virtobot. *a* Tool changing mechanism, *b* retroreflective markers, and *c* needle gripper holding an introducer needle



**Fig. 6** *a* Marker stand with integrated tungsten ball. A retroreflective marker (*b*) can be clipped onto the marker stand (*c*), and the tungsten ball is located at the center of the marker

automatically loaded, and the registration process begins. For the first Virtobot, the manual registration of the dataset reduced the acceptance of the system, and we addressed this problem by introducing automatic registration. By identifying the high Hounsfield unit (HU) values of the tungsten balls that are located inside the reflective markers, the marker positions are known in CT coordinates and can be matched with the marker positions measured by the tracker. If the automatic registration fails, the user is asked to manually identify the marker positions. In the following step, the trajectories are identified by defining a target point, an entry point and the orientation of the biopsy tool. The software gives immediate feedback on the reachability or collision with bony structures, and once all trajectories are defined, the needle positioning is executed by the VCC. After positioning the robot, the correct positioning is ensured by the navigation system, and a correction vector is applied. During robot positioning, a real-time view by the navigation system shows the planned trajectory and overlays the current position of the biopsy module. We implemented a new needle-release motion because the needle could get stuck during the release motion of the robot, which could lead to lower accuracies due to soft tissue movement.

The needle placement accuracy was evaluated using a biopsy phantom. In this phantom, radiopaque, spherical markers acted as targets (Fig. 7), and needle trajectories were planned with the center of the markers as targets. The needles were placed and the accuracy was determined by performing a subsequent CT scan and measuring the shortest distance between the needle axis and the center of the target, using the same approach as it was used for the previous study [3]. This procedure was repeated 22 times, and the needle placement accuracy was assessed.

## Results

The second Virtobot has provided robotic assistance for the automated surface documentation of 24 cases over the past

11 months, and these cases included 17 blunt force injury, 6 gunshot wounds, and one case of sharp force injury. All surface documentations were requested by the legal authorities. In 7 of these cases, the surface documentation is or will be part of a scene reconstruction, requested by the state attorney. For the rest of the cases, the scans were performed for detailed documentation of the superficial injuries. Concurrently, 475 cases have been submitted to our institute for post-mortem examinations with CT scans and autopsy reports; therefore, 5.1 % of our cases require surface documentation. The time required for an automatic photogrammetry was measured to be 4.5 min. Scanning all 25 predefined positions with the optical surface scan takes 6 min.

Furthermore, biopsy tests on the phantom revealed an average placement accuracy of 1.4 mm ( $\pm 0.9$  mm, min 0 mm, max 3.1 mm).

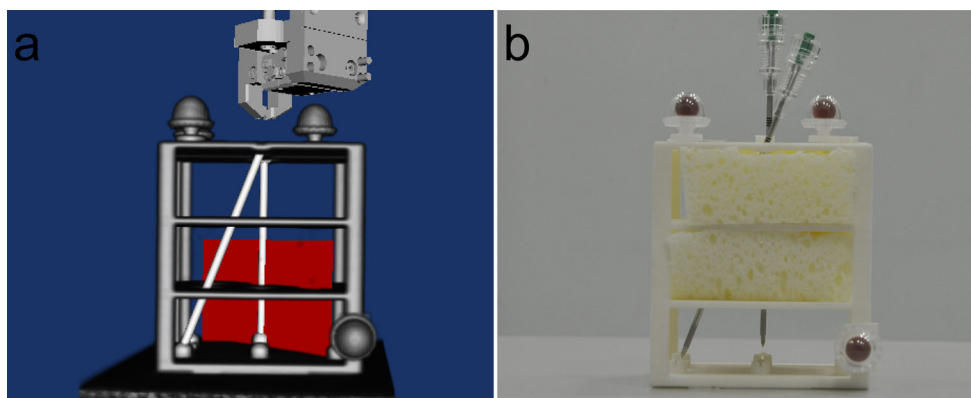
## Discussion

In this paper we present a new prototype of the Virtobot system. This model supports an automatic tool-change mechanism, a new software setup, a passive optical tracker and different workflow optimizations.

The new Virtobot addresses two issues of a virtual autopsy. First, it allows for automatic surface documentation in high resolution with color information, which is a time consuming task if performed manually. Second, it enables the accurate CT-guided placement of introducer needles for subsequent sampling of tissue or liquid for histological or toxicological examinations. The current parking position above the CT scanner allows for the installation of the robotic arm even under tight spatial constraints, and the new software versions enable us to run the entire user interface on one computer, thus further simplifying its usage and reducing costs.

Surface documentation techniques are routinely being used in forensic institutes in Switzerland, and post-mortem surface documentation is used in cases where patterned

**Fig. 7** Needle inserted into needle phantom. *a* Volume rendering of planned trajectories (white lines). Radiopaque spherical markers act as targets. *b* Photo of the final position of the needle in the phantom after placement



injuries are visible on the body surface. The generated 3D data can be either used for pure documentation, which is similar to a digital photo but with geometric properties, or help in reconstructive questions. Examples include traffic accident or crime scene reconstructions, gunshot wounds or bite-mark identification [5, 6, 15]. The surface documentation procedure consists of two main parts: photogrammetry and surface scanning. While the automation of surface scanning using the first Virtobot reduced scanning times, the photos for photogrammetry still had to be performed manually [3]. Because flashlights created unwanted color changes and highlights in the photos, a tripod was also required, which took about 15 min for a photogrammetry per side. Surface scanning (excluding preparation of the body and CT scanning) took 15 min [3]. With the current Virtobot, the documentation of one side of a body is therefore reduced from about 30 min to around 10.

While the Virtobot upgrade reduces the time the body is required to be in the CT room, the entire documentation procedure is still time consuming. This process includes preparation of the body (cleaning, shaving, positioning the body on the vacuum mattress, and application of markers), two CT scans (supine and prone position), documentation of the entire surface, and manual, high-resolution digital photos of wounds, and this entire procedure takes approximately 2–3 h. However, because the caseload in Switzerland is approximately 30 surface documentations a year, these scanning times are feasible and a much higher case load would be possible with the system. With even higher case numbers, further optimizations, mainly in the preparation process, are required. For example, instead of using un-coded reference markers, the known position of the robot during surface scans could be used to fuse the different scans, thus saving additional time.

The current VCC mainly relies on predefined scanning points. If additional scanning points or angles are required, i.e. because of missing information in the 3D model, the robot position can be manually adjusted in the VCC software. For easier handling, it would be desirable to be able to directly define new scanning positions inside the ATOS surface scanning software.

Post-mortem, image-guided needle placement has different uses in forensic medicine. It allows for minimally invasive tissue sampling, liquid sampling, or the placement of guide wires to assist pathologists in finding foreign bodies or small pathologies during autopsy. Histological examinations that are performed on such tissue samples are an important tool for gathering additional data during a virtual autopsy examination. By performing CT-guided needle placement, it is possible to correlate histological findings with visible changes in CT images. Due to their minimally invasive nature, these techniques are also feasible in cases where an autopsy is not permitted, i.e. for

religious reasons. When compared to other needle placement techniques such as CT-guided or navigated needle placement, robotic needle placement occurs independently of the user and requires less training. In addition, there is no radiation exposure to the radiologist.

By optimizing the user interface and introducing automatic registration, the system is easier and faster. By using a new tracker, we could also reduce costs. The new Virtobot increases the average needle placement accuracy from 3.2 to 1.4 mm when compared to the first version [3], and this is mainly due to the automatic registration and manual calibration of the biopsy module. Several factors play a role in needle placement inaccuracies. Technical limitations such as the resolution of the CT scanner, the registration errors, robot placement errors, inaccuracies in the planning process and measurement errors of the tracker, as well as non-technical errors induced by soft tissue movement, add up to the final placement error. We estimate that an accuracy of around 5 mm is sufficient to target most of the forensically relevant findings [3]. By reducing the placement error induced by the system, we now can better compensate for soft tissue movement errors.

In the future, the biopsy procedure can be improved on the hardware and software side. In the current version, the robot places the introducer needles. While this is versatile and allows for biopsy, liquid sampling and the placement of guide wires, an automatic tissue extraction mechanism would be desirable to further increase the speed and minimize contact with potentially infectious body fluids. In the planning and navigation station, an automatic suggestion for potential entry points or the fully automatic planning of trajectories for general organ sampling could speed up the planning process. Furthermore, by using MRI/CT co-registration techniques, it could be possible to allow for tissue sampling based on MRI images.

## Conclusion

The second prototype of the Virtobot system is an upgrade of the first prototype and mainly focuses on streamlining the workflow, increasing the level of automation and making user interface easier to manipulate. These upgrades make the Virtobot a potentially valuable tool for case documentation in a scalpel-free setting that only uses imaging techniques and minimally invasive procedures.

## Key points

1. The Virtobot system allows for automatic surface documentation and image guided robotic needle placement.



2. The second Virtobot provides better usability, faster surface documentation and higher needle placement accuracies.
3. The Virtobot is routinely used for post-mortem surface documentations.
4. The Virtobot is a potentially valuable tool for scalpel-free medicolegal investigations, only using imaging techniques and minimally invasive procedures.

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**Conflict of interest** Integrated Microsystems Austria GmbH is planning to commercialize the Virtobot system.

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